The Evolution of Intel's Copy EXACTLY! Technology Transfer Method

Chris J. McDonald, Intel SEMATECH

Index words: copy exactly, technology transfer

Abstract

Semiconductor manufacturing is characterized by very complex process flows made up of individual process steps, many of which are built to very close tolerances. Furthermore, there are complex interactions in these process flows, whereby each process step can affect many other steps, and each final device parameter might be determined by the results from many inputs. This level of complexity is increasing with each new technology generation. Items that were once considered second-order effects, such as barometric pressure and ultra pure water temperature, are now important variables affecting process results.

The costs of technology development and capital equipment for production are very high and are increasing with each generation, thus making technology transfer very important. Once a new process flow and product portfolio have been developed, it is essential that the technology transfer to mass production take place as quickly as possible, without disruptive quality issues, and with the highest possible yield. No time is available to debug new problems that occur during the transfer.

The traditional technology transfer approach often allows many equipment and process changes to be made. These changes are intended as improvements in the process, or they are for the convenience of the production factory, which may be already producing other products. As semiconductor technology becomes more complex, these changes have resulted in unforeseen problems that cause production start-up delays and inferior results.

The Copy EXACTLY! philosophy and systems were developed [6] in order to minimize the time required for a technology to be transferred and to ensure product quality and yields are not compromised. The methodology has been improved and refined, and has become an important element in Intel's overall manufacturing strategy [1]. This paper describes the Copy EXACTLY! methodology and the increase in technology transfer performance that it has brought about. Some side benefits of this methodology are also discussed.

Introduction

Table 1 shows the typical technology transfer approaches used over the last ten years or so. At the 1.5-micron generation, process flows were much simpler than they are today. A small band of technical experts would typically be employed to orchestrate a successful technology transfer. Generally there would be few ground rules. Since there is always a lengthy "certification" or "qualification" exercise to prove product quality and reliability, the transfer from R&D to manufacturing, or to a new factory, offered the opportunity to introduce improvements to the equipment and process. The latest model equipment or even a new vendor might be chosen. Process recipes could be changed to improve them. In the case of an existing factory picking up a new process flow, changes were made to match existing processes and methods to improve efficiency and productivity. Sometimes, a wafer size conversion would even be made at the same time, involving many changes. Overall, however, the number of variables was relatively small, which made it simple to trouble shoot any results that did not come out as expected.

Technology Generation	Transfer Strategy	Comments
1.5 micron	"Make It Work"	Small band of engineers. Few ground rules needed.
1.0 and 0.8 micron	"Process Output Matching"	Copy selectively. Match to existing factory conditions.
0.5 micron	"Copy EXACTLY!"	Copy everything that might affect the process.
0.35 and 0.25 micron	"Systems Synergy"	Copy all manufacturing systems.

Table 1: Technology transfer strategies

For the one-micron generation, technology transfer started to get more complicated. A structured methodology was needed, whereby each process step would be measured to ensure it matched a target value or complied with a set of specification limits [2] [3]. Most projects, however, only fo-

cused on matching device and final product parameters. As long as these were correct, changes would still be introduced as a part of the transfer process.

For the sub-micron generation, the above approach has had its share of problems. There are many more process steps today, and many of them are made up of several components. For example, a typical metal or dielectric layer is now a sandwich of multiple layers of different materials and compositions. Very fine device structures are subject to different effects, such as inter-layer stresses and adhesion. Phenomena that were once considered second-order effects now have a significant effect on the process result. Among these are barometric pressure and ultra pure rinse water temperature. In general, the process is manufactured with much closer tolerances, increasing the importance of process control. Even the length of an electrode cooling hose has had a catastrophic effect, but this is a very subtle variable to find. With larger die sizes, defect control becomes even more critical, and the way the process is actually run becomes a more important factor. An example is preventive maintenance intervals and workmanship. Many of the factors just mentioned are difficult to measure and quantify, which makes them dangerous "unknowns" during a technology transfer project. When many changes are made, the risk of something going wrong is greatly increased. Moreover, if something does not come out as expected, the number of variables that have to be studied when trouble shooting the problem is greatly increased. The amount of experimentation and therefore, time, required to find the problem increases as a power function of the number of variables involved. If the problem is a showstopper, for example affecting the product reliability, the end result is a costly delay. Even if this is not the case, yields may be depressed for an extended period.

Figure 1 shows one example of using the traditional approach for the 1.0-micron technology generation. The die per wafer yield is one of the most important variables in wafer fabrication and is used in this example. (The graph is normalized for die size). Other factors affecting product performance or manufacturing efficiency showed similar trends. The first production factory in this example, which was a brand new facility, obtained results that reasonably matched the parent R&D line. You can see the yields improve further as improvements were made and the organizations moved down their learning curves. Note, however, the divergence at the end of Year 2. The technology transfer results were good [2]; however, yields diverged as the R&D line focussed on yield improvement, and the manufacturing line concentrated on increasing volume.

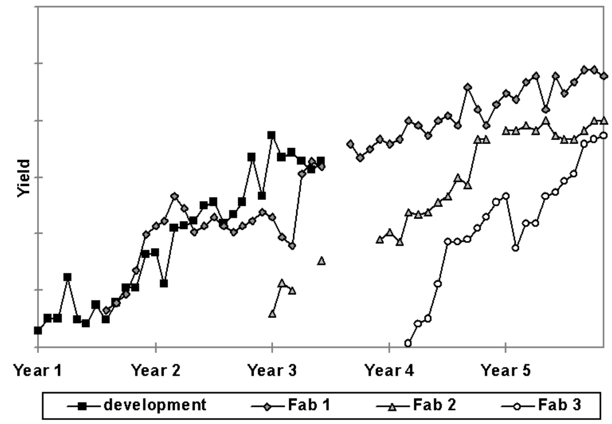

Figure 1: Traditional technology transfer method for the 1.0-micron generation

Eventually the yields did converge. The second and third factories, which were already manufacturing different process flows, made many changes to the process and equipment and used their existing manufacturing methods. It took several months of task force actions to catch up, by which time the first factory was moving further ahead. In effect, the same learning curve was repeated independently by every factory. For the 0.8-micron generation, a new factory start up and a new product introduction were delayed by three months while a device reliability problem was solved, and it took approximately one year to obtain equivalent yields [4].

Method

For sub-micron technology, it was realized that a fundamentally new approach would be needed in order to accomplish an "order of magnitude improvement" in the effectiveness of technology transfer. The Copy <u>EXACTLY!</u> philosophy and systems were developed [5] [6] for the 0.5-micron generation, and they have become a key part of Intel's manufacturing strategy [1]. The capital letters, underline, and exclamation point emphasize the paradigm shift that is required to transfer technology using this method.

Copy <u>EXACTLY!</u> Philosophy

Stated in its simplest form, "everything which might affect the process, or how it is run" is to be copied down to the finest detail, unless it is either *physically_impossible* to do so, or there is an *overwhelming_competitive benefit* to introducing a change. This philosophy differs greatly from the traditional method. In practice, there are always some issues

that crop up and prevent an exact copy being made, so it was important to provide for making some changes in a controlled fashion without opening the field too much. For example, in Europe the supply voltage and frequency can be different than those in the U.S., so these had to be accommodated. Moreover, engineers are typically trained and rewarded for making improvements, which in the semiconductor industry implies orchestrating change. Even the educational system stresses independent work, and copying is seen as cheating. Making a philosophical statement is obviously much easier than implementing it within a large team of R&D and manufacturing engineers. Therefore, a comprehensive set of systems was put in place to ensure it would be implemented, and this set of systems is discussed in the next section.

Systems

The systems that were implemented are as follows:

Four level matching: Traditionally, it has been considered acceptable if the final product parameters are matched between the R&D line and manufacturing. However, the Copy EXACTLY! approach requires four levels of matching. These are illustrated in Figure 2.

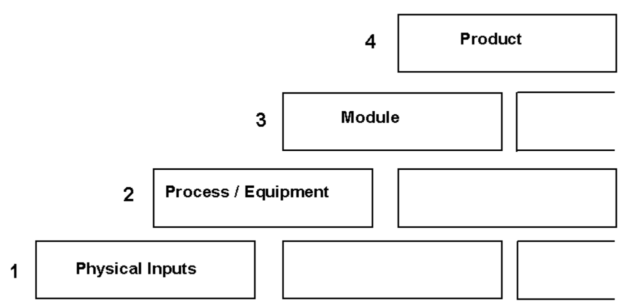

Figure 2: Four-level matching

- Firstly, the physical inputs have to be matched. These are the energies and materials supplied to the process chambers: for example, gas flows, temperatures, pressures, RF power, and so forth. These might be supplied to the equipment by external sources or be generated within the equipment itself. Everything about the equipment and its installation must be an exact copy down to the diameters of piping and the number of bends, board revisions, software, etc. The settings for these parameters and anything that might affect them are copied. Standards are generated to allow measurement and comparison, and the values are measured and matched.
- Secondly, data is collected at the process step output level on parameters such as film thickness, resistance, composition, etc., and they are compared to results at the R&D site.
- Thirdly, a comparison is made at the module level, using test structures such as oxide capacitors and metal serpentine patterns.
- Fourthly, the actual product characteristics are measured and matched.

Formal statistical tests are used at each level. If the match passes these tests, then we proceed to the next level and so on. If the match does not pass the tests, the root cause must be found and eliminated. If it can't be found, trouble shooting occurs to find out which of the previous level inputs is responsible because, despite best efforts, something may have been overlooked. It is vitally important to avoid the temptation to make a compensating adjustment. Due to the complexities involved, an adjustment may result in an interacting parameter, possibly something not measured, being mismatched.

A change control system: Most factories have some kind of approval process for making changes to a production process, either in the form of a sign-off list or a formal change-control committee. Generally there is some kind of record of the data showing the benefits of the change. The R&D line continues to make improvements to finish off the technology development and, in many cases, they may also run some level of samples and production output. With Copy EXACTLY! change control is started before technology transfer, and all changes are implemented directly into both the R&D and production lines within one week, or according to an approved schedule. The pace of R&D work is not allowed to slow, so careful planning is required to ensure the new line is ready to accept the changes in real time. Any engineer from the manufacturing line who has a good idea for improvement is encouraged to pursue it. The only difference from the traditional approach is that the idea must be implemented simultaneously at all sites. The change control board is responsible for the smooth operation of the system, which includes ensuring that the additional requirements do not slow down the rate of improvement.

Equipment difference form: In the Copy EXACTLY! system, each first piece of equipment in the new factory or on the new process flow in the existing factory is treated as a change, subject to change control. Audits are conducted and an Equipment Difference Form is prepared from each. This form documents the actual difference, what risks it might pose, and the corrective action plan. This is formally reviewed by management.

Supplier education: Equipment and materials' suppliers are constantly improving their products in response to demands from the semiconductor industry for improvement. These changes are still desirable; however, with Copy EXACTLY! they are first introduced into the R&D line and from there transferred to production. The suppliers are a vital part of the technology transfer and need to be thoroughly educated on the new concept and systems.

Audits: An audit is a formal procedure whereby engineers from R&D and from production audit both lines. These audits are required and scheduled as part of the technology transfer and are ongoing for a period thereafter. A report is written for each audit, detailing plans to correct all differences found.

Joint specifications: Since the equipment, process recipes, and procedures are all the same, there is no reason why the documents provided for training and manufacturing operations cannot be the same. These are not copies; they are the same documents, either paper or electronic.

Questions and answers (Q&A): Different engineers tend to interpret the Copy EXACTLY! message in different ways. For example, some engineers might say, "Surely if I make sure the pressure is the same, then it doesn't matter if I use a different pump with less bends in the vacuum line." The answer to this particular question is "*Yes,* it does make a difference, and *no,* it's not ok to make a change." The rationale is that you might be able to get the same result under ideal conditions, but the only way to guarantee you will always get the same results, both steady state and transients, under all possible conditions of environment, age, etc., is to copy the configuration exactly. To deal with this type of question, a detailed Q&A list was prepared and communicated to all engineers involved on the project.

Systems Synergy

The scope of copy EXACTLY! for the 0.5-micron technology was for the most part limited to anything that might have an impact on the process, or how it is run. The motivation was to guarantee equivalent yields, starting with the first wafer, and to ensure there were no reliability problems to delay production. One recommendation [7] from this program was that the concept could be extended into other areas as a way to further accelerate new factory start-ups and the manufacturing ramp of new-generation technologies.

The 0.35- and 0.25-micron generation technology transfers [8] took the Copy EXACTLY! method a step further into what has been described as total "Systems Synergy," where almost every aspect of the fabs are identical at multiple geographic sites. The 0.8- and 0.5-micron generations both had a "virtual factory" organization structure and a series of committees to set the strategic direction and manage the technology. For the 0.35- and 0.25-micron technology, this has been expanded: a Steering Committee at the plant manager level sets the overall direction, Joint Engineering Managers' Teams manage the technology, and individual Joint Engineering Teams work the details at the process and equipment level. Similar structures exist in other areas, such as Manufacturing Operations and Automation, and a "Joint Synergy Team" manages the overall system.

Results

Figure 3 shows some typical results obtained from Copy EXACTLY! Two new factories were successfully brought on line with the same yield results as the parent R&D line. Furthermore, all three lines were able to improve their yields together by implementing improvements simultaneously. Other parameters such as product quality and reliability and manufacturing efficiency also matched very closely.

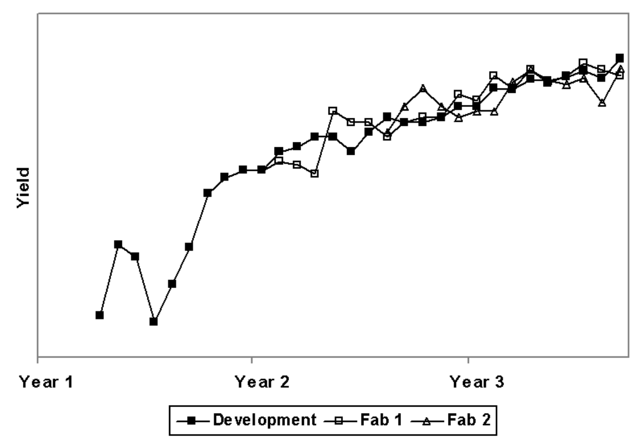

Figure 3: Copy EXACTLY! technology transfer method for the 0.5-micron generation

As always with projects of this magnitude and complexity, there were some issues encountered along the way. For example, a very subtle problem affecting the integrity of the sub-micron metal lines was found. However, since the process had been copied so precisely, trouble shooting became an exercise in revisiting the exceptions that had been made and auditing to look for unforeseen errors in copying. In this example, two variables were identified as suspects, and a simple experiment on test wafers identified the cause within a week. A simple typographical error had been made in entering a process recipe. The problem was very subtle and would have taken many weeks to identify if a traditional transfer approach had been used. In addition, areas for improvement

in the technology were known and found in both sites. Since no new problems were introduced as a result of the technology transfer, the number of engineers and other resources available for basic improvement work was greatly increased. Moreover, the overall technology transfers to two new 0.5-micron factories were accomplished in record time with very few problems along the way.

Figure 4 shows the results obtained on the 0.25-micron technology generation, using copy EXACTLY! and Systems Synergy.

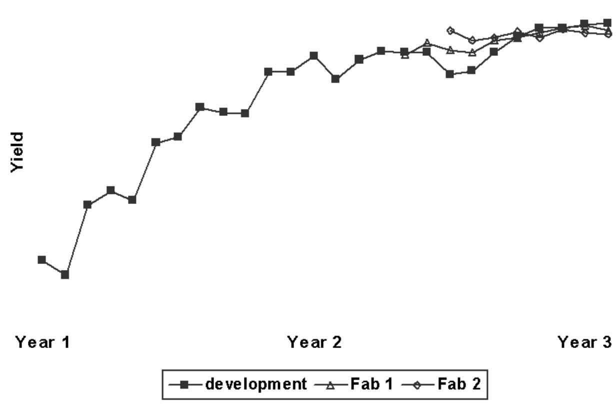

Figure 4: Copy EXACTLY! technology transfer method for the 0.25-micron generation

It is now routine for new Intel factories or new technologies that were transferred to obtain equivalent yield starting with the first check-out wafer. Production quantities of products are started immediately since there is such confidence the product will be good.

Discussion

The difficulties in implementing this new philosophy and system are not to be underestimated. Any major project, such as a new factory or new process flow in an existing factory, is started with the ambition to get the best ever results. Engineers are trained and rewarded for doing improvement projects, and product re-qualification affords them such an opportunity. The natural tendency is thus to use the new start-up as an opportunity to implement improvements. To change the mind set of a large body of technical experts requires a very simple message, consistently delivered, and backed up by a set of systems that make it difficult to behave differently from the desired state. With Copy EXACTLY!, the message to the production engineers was to achieve the best ever replication in the fastest possible time, and it will be considered the "best ever." Once the new products are up and running, with good stability and in high volume, the production line engineers earn the right to take a leadership role in making improvements. In the meantime, ideas are still welcome, but they are implemented through the R&D organization and at the same time at both sites. The R&D engineers also need to make some sacrifices. To make changes they now need the support of the production line engineers.

The results obtained clearly show the merit of the Copy EXACTLY! philosophy and systems. The process flow was transferred to two new factories in record time with equivalent yield and other indicators, and with no product quality issues. The new lines were able to precisely intercept the technology learning curve.

A number of other benefits were also realized and are as follows:

Customer acceptance: Many major customers for integrated circuits are well aware of the risks in changing manufacturing plants and will typically demand the opportunity to re-qualify a second source. If the supplier has a high credibility rating, this may simply require a study of all the data from the new line. However, in many cases the customer may want sample devices to submit to his/her own testing, or to a third party laboratory. He/she may also require a site visit and an opportunity to audit the new line. In all cases there will be additional costs and delays in time to market. However, once the customers understood the Copy EXACTLY! method, many of these concerns, costs, and delays were eliminated.

On-going mutual synergy and shared learning: In the example outlined here, the R&D line continued to manufacture the new products along with the two manufacturing lines. By keeping the process in lock step at all three sites it was possible to share the improvement projects among them. Improvements were characterized in one site and transferred to the others with minimal effort. In effect, the number of engineers per process step or per area for improvement is increased, as is the number of improvement ideas generated.

Manufacturing flexibility: With three sites running the exact same process, products were easily transferred back and forth with no re-qualification, other than checking the mask set. Using free capacity at another site has also solved manufacturing bottlenecks.

Conclusion

The Copy EXACTLY! method has proven itself as a technique for semiconductor technology transfer. A new process flow and products can be introduced to production in minimum time with equivalent yields and without the introduction of product-quality issues. Both manufacturer and customers can reduce their time to market. This approach could equally be employed in other industries where the technology is complex and has many interacting variables affecting

the end result. The concept has been successfully expanded to cover all systems used in manufacturing.

Caution

Copy EXACTLY! is a powerful method for technology transfer, but should not be applied during technology development. By definition, technology development means taking new processes and improving and integrating them to create a new generation process flow with greater capabilities. While it may be decided that some existing process modules and equipment can be reused as they are, in general, technology development requires great creativity and innovation. Technology development would be dampened by the rigid discipline required during technology transfer and manufacturing.

High-volume manufacturing also demands a high degree of change. Yields must be continuously increased, efficiencies improved, and costs reduced. It is vitally important that the systems used to manage change strike a good balance between the discipline required to keep the factory under control and the creativity and innovation required for continuous improvement. Manufacturing improvement systems need to be very fast-moving and flexible. Multiple factories running the same process and products should remain matched, but not necessarily identical at all times. New approaches should be tested in one site and proliferated to others when proven.

Finally, the Copy EXACTLY! method is designed to match all factors that impact the process or how it is run. Other systems might benefit from matching, but time and money should not be wasted on matching factors that have no impact on the overall process.

Acknowledgments

The author would like to recognize Tom Hartman for his leadership through two new factory start-ups. The author also acknowledges Bob Jecmen and Bruce Leising for their sponsorship in the implementation of these new approaches, and for their support in the publication of this paper.

References

[1] G.H. Parker, "Intel's Manufacturing Strategy," presented at the *5th International Symposium on Semiconductor Manufacturing.*

[2] C.J. McDonald, "Fab 9.1 Start-Up Methodology." *Intel Internal Document,* June 1988.

[3] M. Bohr and S.Ruska, "P650 Transfer Methodology Proposal," *Intel Internal Document*, December 1989.

[4] S. Ruska, "Post-Mortem of Fab 9.2 Yield/Undercut Issues," *Intel Internal Document*, December 1991.

[5] C.J. McDonald, "Fab 10 Start-Up Methodology – Copy EXACTLY!," *Intel Internal Document,* February 1992.

[6] C.J. McDonald, "Copy EXACTLY! A Paradigm Shift in Technology Transfer Method." Presented at the *IEEE Advanced Semiconductor Manufacturing Conference*, 1997.

[7] J. Multani, C.J. McDonald et al., "P852 Virtual Factory Vision Through Copy EXACTLY!." Presented at the *Intel iMEC Conference*, 1994.

[8] G. Gimpelson et al., "Rapid Technology Transfer: BKM's from the P856 Process Transfer." Presented at the *Intel iMEC Conference*, 1998.

Author's Biography

Chris J. McDonald holds a B.Sc. in electronics from the University of Southampton, UK and an M.Sc. in electrical engineering from the National Technological University, USA. He is a sixteen-year employee of Intel, currently assigned to SEMATECH where he is director of the Advanced Technology Development Facility. His other positions included that of manufacturing manager and yield/Q&R manager for the start-up and ramp of Intel's high-volume manufacturing facility in Ireland and a process/equipment engineering manager in Albuquerque. He has twenty-four years experience in semiconductor process development and manufacturing, and he has worked in all areas of wafer fab engineering with a wide range of memory, microprocessor, and other products. His e-mail is chris.mcdonald@sematech.org or chris.mcdonald@intel.com.